Exercise 12

Waves in Shallow Water and Beach Erosion

OBJECTIVES:

- To understand the characteristics of wind waves as they move from deep water to shallow water.
- To discover what causes waves to peak and break as surf and how they generate longshore currents and dangerous rip currents.
- To investigate the dynamics of sand, beach drifting, and beach erosion.

In Exercise 11 we discussed the origin and nature of deep-water waves in the open ocean. When these waves move into shallow water and strike the shoreline a transformation takes place, producing breakers, or surf, which can create or destroy beaches. Whereas most of us regard a beach as a place of recreation where we can relax, watch the surf, and get a tan, geologists and engineers recognize beaches as the last rampart of protection of the land against the sea. If we do not manage this resource wisely, the contest between human ingenuity and the ocean's relentless pounding will be won by the sea. Beaches along both coasts of the United States have been deteriorating badly in the course of the past few decades, and in some places they have completely disappeared. Where this occurs, valuable recreational land is lost and coastal-zone property endangered.

Shallow-Water Waves

Shallow-water waves are defined as those that are traveling in water whose depth is half the wavelength or less. Recall that the water motion in a deep-water wave is circular and that the diameter of the orbits decreases downward until, at a depth equal to about half the wavelength, water motion ceases. However, when a wave moves into shallow water, a drastic change takes place. The orbits of water particles at depth become flattened, and those in contact with the sea floor simply move back and forth (Figure 12-1). The wave is said to "feel the bottom" and, as a result, the wave velocity and length decrease, and the wave form steepens until it becomes unstable and spills against the shoreline as breakers, or surf. At this point the oscillations of the water particles cease and the water motion is all in one direction, toward the beach. Figure 12-2 shows this transformation from swell to shallow-water wave to surf. Whether a wave is classified as a shallow-water one or not depends on both the wave itself and the basin within which it is traveling. Figure 12-3 shows the relationship between wave period and water depth. Because the length of a wave is proportional to the square of its period, the diagram also shows the relationship between wavelength and depth of water. We see that very short-period waves, such as ripples, are deep-water waves even in relatively shallow water. Sea and swell are also deep-water waves in water from about 100 to 1000 feet deep. However, in water shallower than 100 feet, sea and swell become shallow-water waves. In the deep ocean, with an average depth of about 15,000 feet, all waves with periods greater than 80 seconds are shallow-water waves. In this category we find the tides and tsunamis, or so-called tidal waves. Tsunamis are long-period sea waves produced by submarine earthquakes, volcanic eruptions, or landslides.

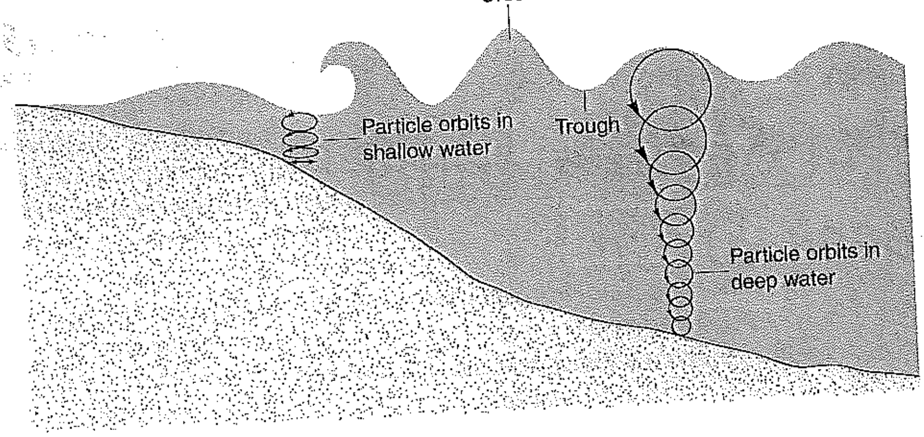


***Figure* 12-1** When waves approach a shallow bottom near the coast, they slow and steepen, and the circular orbits flatten and become smaller. The diagram shows considerable vertical displacement. [After R. A. Davis, Jr., *The Evolving Coast*, Scientific American Library, W. H. Freeman and Company. Copyright © 1997.]

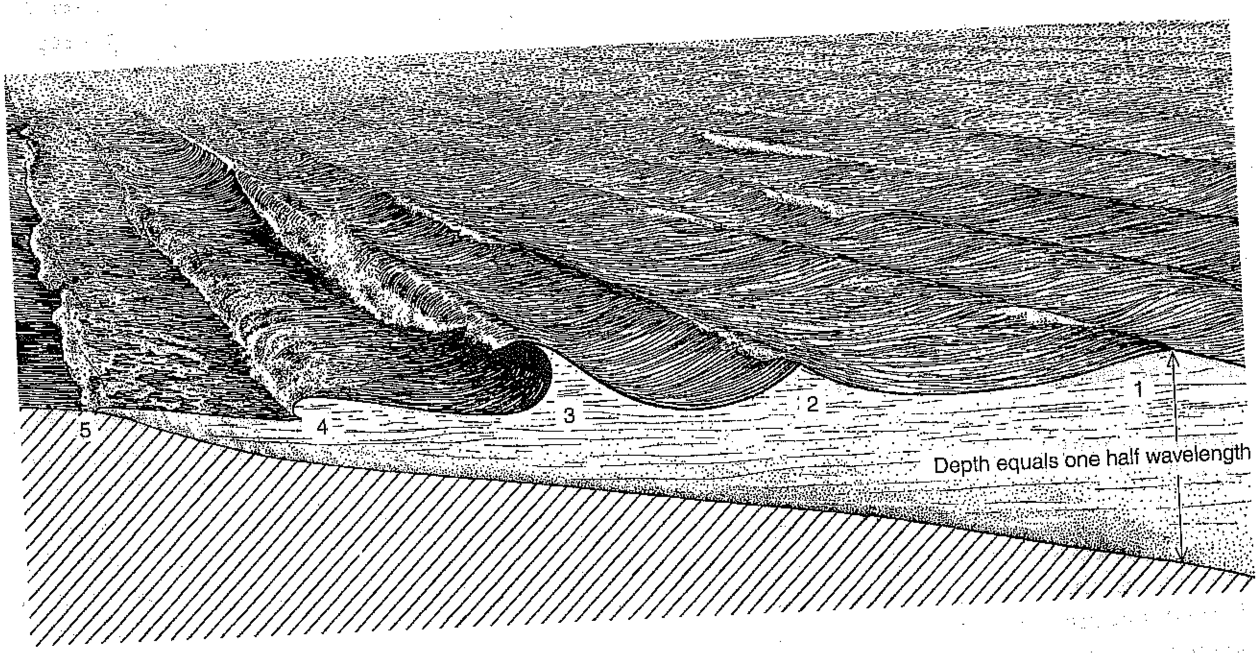


***Figure* 12-2** (1) A wave breaks up at the beach when swell moves into water shallower than half the wavelength. (2) The shallow bottom raises wave height and decreases length. (3) At a water depth of 1.3 times the wave height, water supply is reduced, and the particles of water in the crest have no room to complete their cycles; the wave forms and breaks. (4) A foam line forms and water particles, instead of just the wave form, move forward. (5) The low remaining wave runs up on the beach face as "swash," or uprush. [After W. Bascom, "Ocean Waves." Copyright © 1959 by Scientific American, Inc. All rights reserved.]

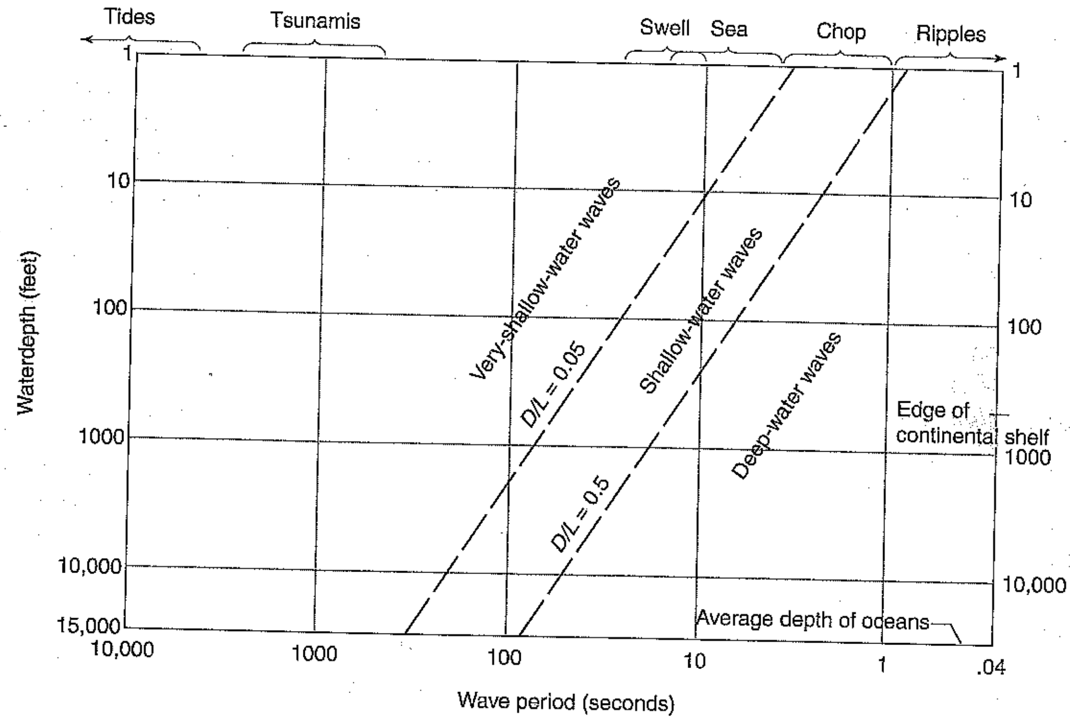


Figure 12-3 Wave characteristics. [After W. Bascom, *Waves and Beaches.* Doubleday and Company, New York, 1964.]

They may travel unnoticed across the ocean for thousands of miles from their point of origin and build up to great heights over shallow water.

Table 12-1 shows the relationship between selected wave periods, the calculated wavelength and wave velocity, and the water depth at which the wave feels the bottom or becomes a shallow-water wave. Note that wind-generated waves with periods greater than 14 seconds are capable of moving sediment at depths as great as the edge of the continental shelf. Most wind waves have periods between 5 and 25 seconds.

TABLE 12-1

The relationships between selected wave periods, calculated wavelengths and velocities, and water depths at which wave feels bottom

Wave period (seconds)	Wavelength* (feet)	Approximate velocity (miles per hour)	Water depth† (feet)
6	184	21	92
8	326	28	163
10	512	35	256
12	738	42	369
14	1000	49	500
16	1310	56	655

*Length is equivalent to 5.12 times the wave period squared.
†Depth is equivalent to half the wavelength.

Wave Refraction

Shallow-water waves are subject to **refraction** over humps or depressions of the sea floor, and to **reflection** from seawalls or breakwaters. Refraction occurs when a wave moves into shallow water at some angle other than parallel to the shoreline. The part of the wave crest in the shallowest water is slowed the most, whereas the part of the wave in deeper water moves forward at a higher velocity. The result is a bending of the wave crest and a concentration or dissipation of energy at the shoreline. An example of a refraction pattern at sea is shown in Figure 12-4. We can determine the relative amount of concentration or dissipation of wave energy by drawing lines perpendicular to the wave crests, known as **orthogonals,** on a diffraction diagram. The wave's energy, or its ability to do work on a shoreline, is the same between orthogonals drawn at equally spaced intervals along the wave crest. By tracing the orthogonals shoreward on the crests of successive waves of selected periods or lengths, we can determine how wave energy is concentrated or dissipated at the **surf zone** (Figure 12-5). The **wave energy coefficient,** *e*, which is the relative amount of concentration or dissipation of energy, may be calculated by simply dividing the distance between two orthogonals at the shoreline by the distance between the same two orthogonals in deep water. When waves are focused by wave refraction on a point, as in Figure 12-5, the distance between adjacent wave orthogonals at the shore decreases and e becomes less than 1. In contrast, when wave energy is dissipated, as along the beach in Figure 12-5, the distance between adjacent wave orthogonals at the shore becomes greater, resulting in e greater than 1. Tracing wave orthogonals shoreward thus provides an estimate of the relative energy expended on equivalent lengths of the shoreline. Low-energy shorelines have $e > 1$ and

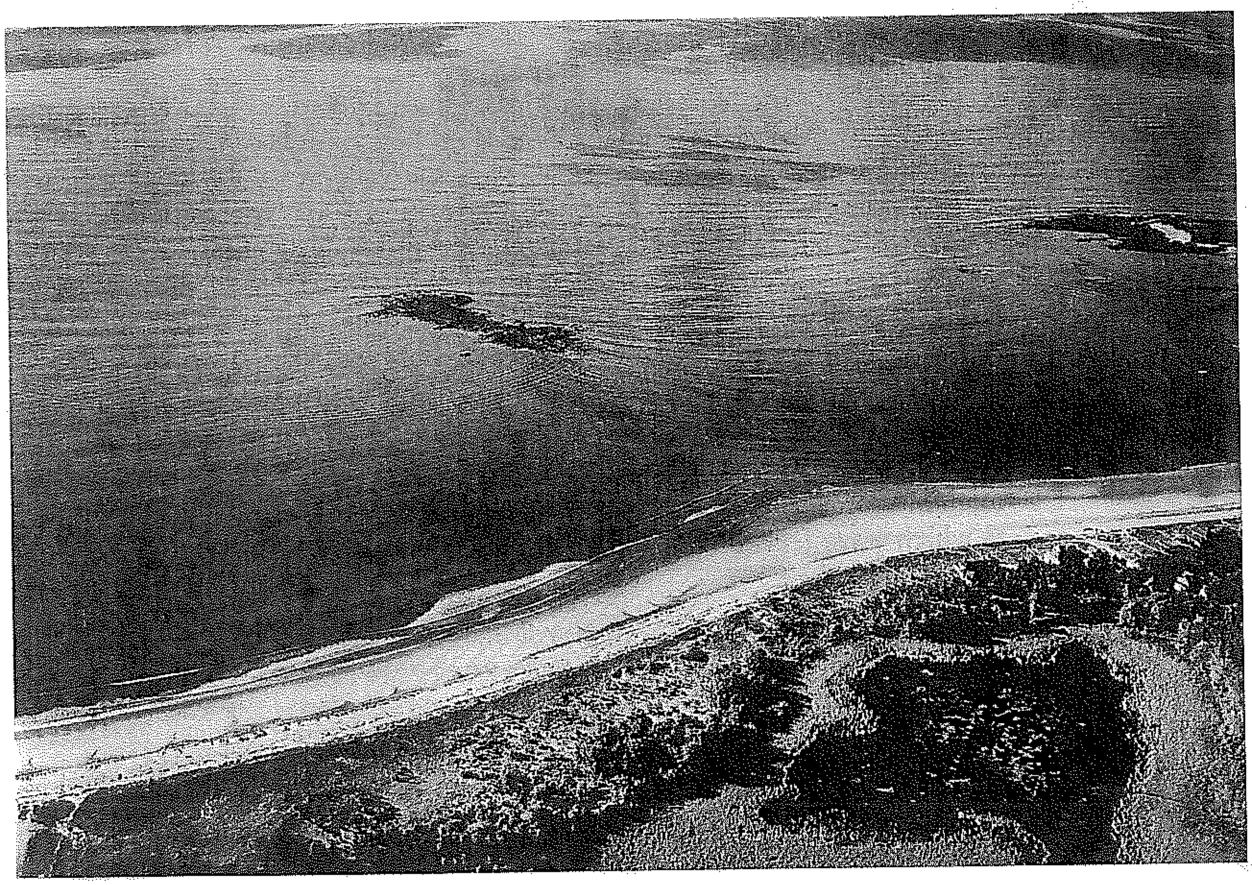


Figure 12-4. Wave refraction associated with a small rocky island 1 mile north of Prouts Neck, Maine. [From John Shelton, *Geology Illustrated*. W. H. Freeman and Company, Copyright © 1966.]

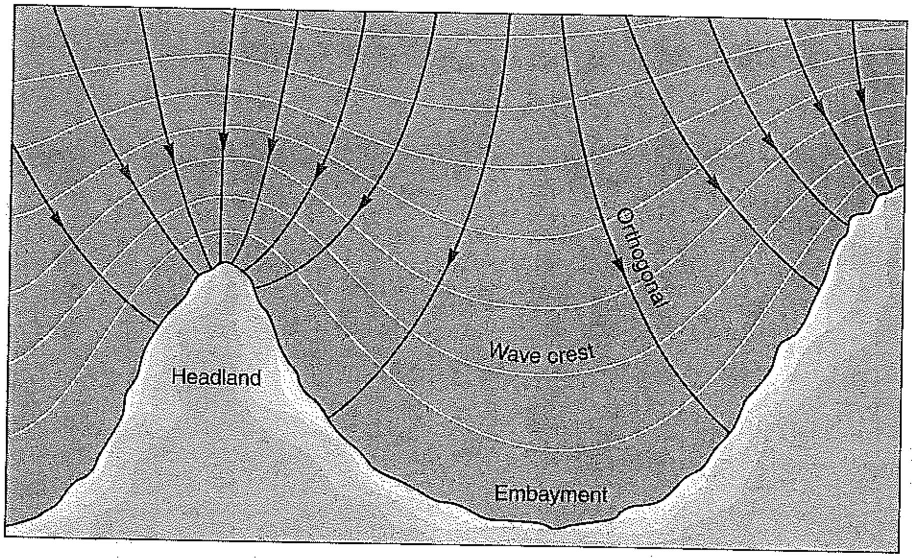


Figure 12-5 This wave refraction diagram shows how the energy of the wave front is concentrated by refraction around the small headland area. The same amount of energy enters the bay, but is spread at the beach over wide areas. The horizontal lines are wave fronts; the vertical lines (orthogonals) divide the energy into equal units for purposes of investigation. Such studies are vital preliminaries to design of shoreline structures. [From R. A. Davis, Jr., *The Evolving Coast,* Scientific American Library, W. H. Freeman and Company. Copyright © 1997.]

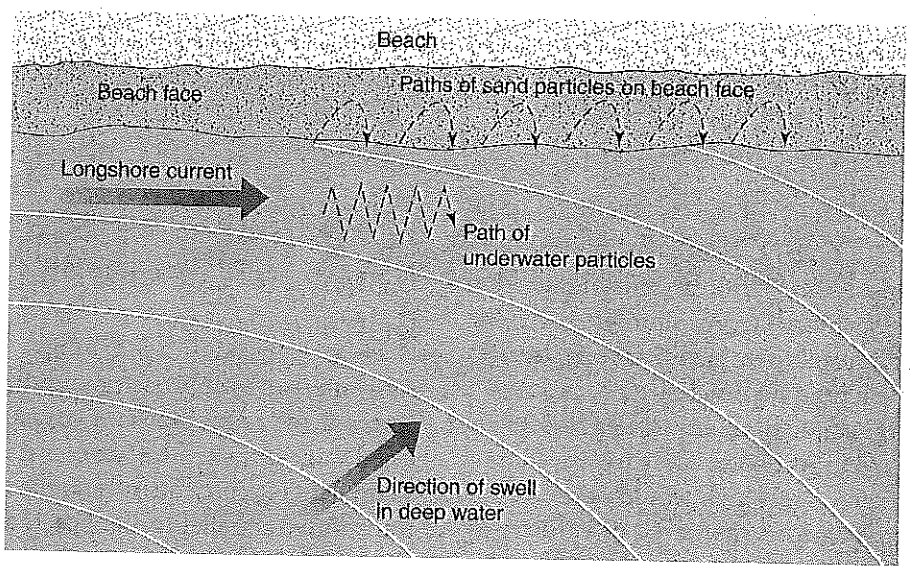


Figure 12-6 Longshore currents flowing parallel to the beach are formed when waves approach the beach face at an angle. Incoming waves carry sand grains up the beach face at an angle, but backwash from the wave returns the grains directly down the face to the surf zone. This alternating motion causes the zig-zag pattern seen in the figure, and results in movement of sand along the beach face by the wave-generated longshore current. [After W. Bascom, "Beaches." Copyright © 1960 by Scientific American, Inc. All rights reserved.]

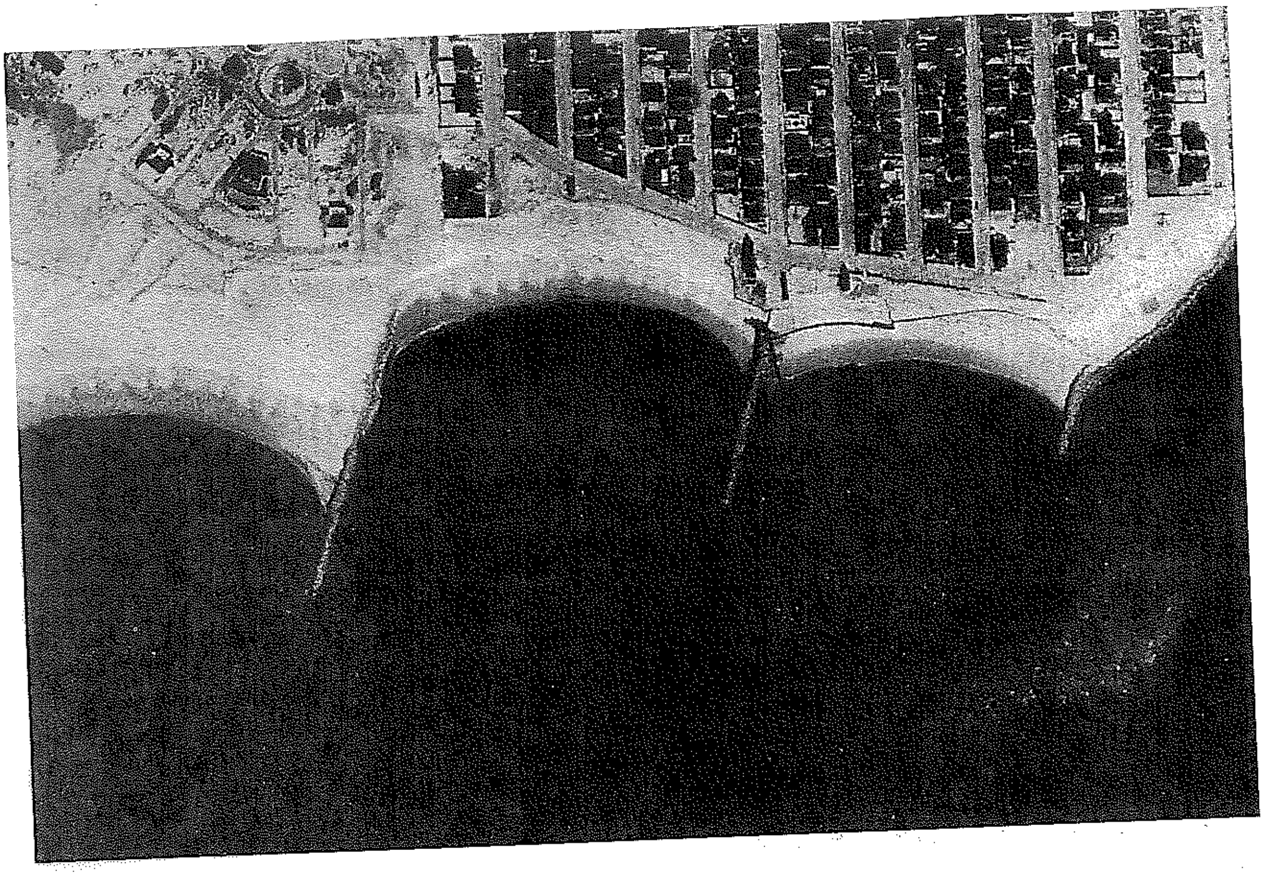


Figure 12-7 Groins, which are dams of wood, stone, or concrete, are built perpendicular to a beach to trap sand. The groins in this photograph are on the Atlantic Coast at Point Lookout on Long Island. What is the direction of longshore current here? [From W. Bascom, "Beaches." *Scientific American.* Copyright © 1960, Volume 203, Number 2, p. 90. All rights reserved.]

are usually depositional, with a sandy beach. On the other hand, high-energy shorelines having $e < 1$ are erosional and may have a gravel (shingle) beach, or a sea cliff and no beach.

The height of a breaker is approximately equivalent to 0.78 of its depth. Thus we would predict that a breaker 7.8 feet high would occur in water 10 feet deep, provided that swell of sufficiently long period were approaching the shoreline. This type of approximation is important in determining the height that piers should be built above mean high water or some other datum. Obviously fishing or commercial activity from a pier 15 feet high would be impeded if the pier were exposed to 18-foot waves (water depth about 23 feet).

Longshore Currents and Littoral Drift

As a rule, waves approach the shoreline at an angle and are refracted; however, because refraction is usually incomplete, the waves strike the shore at a slight angle. Consequently some of the water is transported parallel to the beach and a weak **long shore current** (which flows parallel to the shore) is created (Figure 12-6). The current is like a river on land, and is capable of moving sand along the beach, a process known as *beach drifting*. The earth material moved along the beach by the longshore current is known as **littoral drift.** When an obstruction, such as a groin or jetty, is placed in the

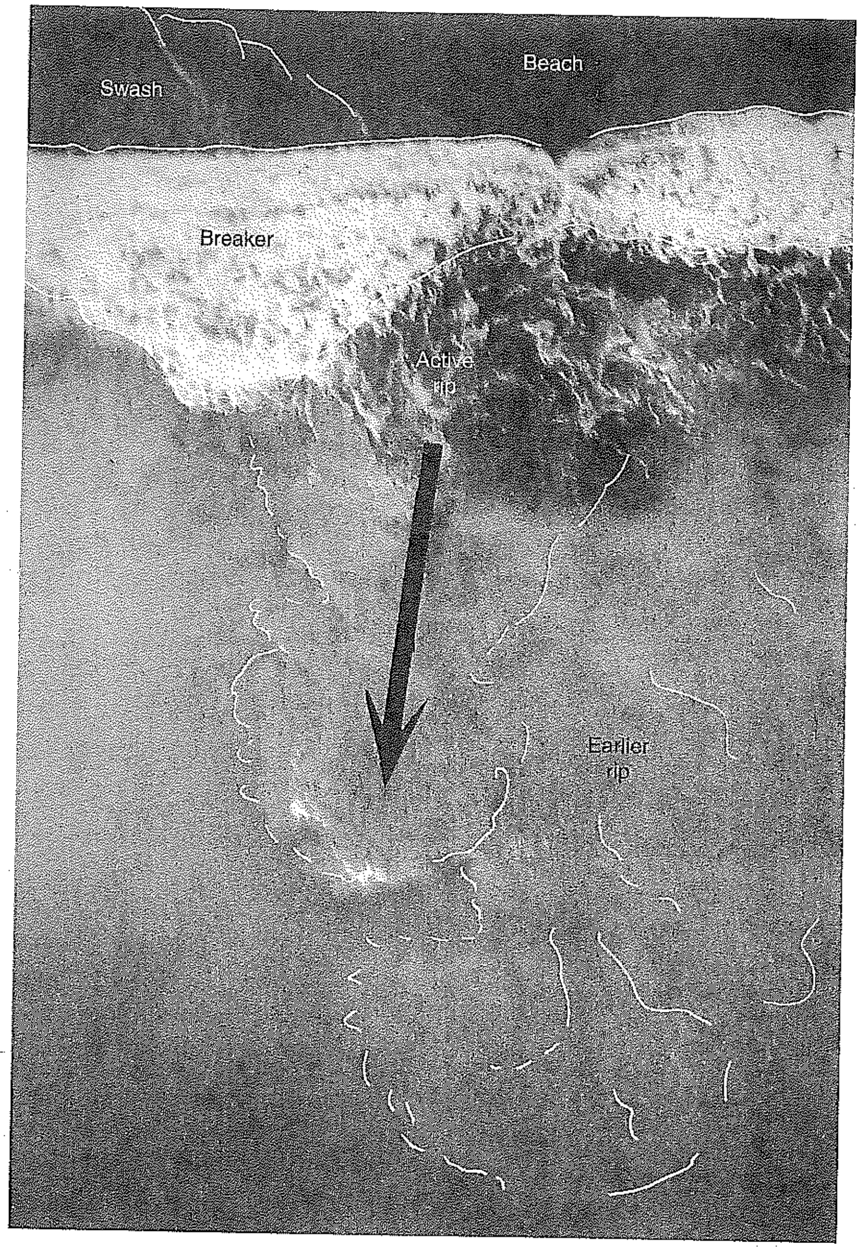


Figure 12-8 Rip currents in the breaker zone near Carpinteria, California, in February 1969. Two pulses of flow can be seen: an earlier jet is seaward and deeper then the active jet. Each pulse is probably the product of a series of breakers. The older pulse is the result of rip generated a few minutes earlier. [Donn Gorsline]

path of the current, a buildup, or accretion, of littoral drift results on the upstream side and erosion occurs on the downstream side (Figure 12-7). The extent of this accretion and erosion depends on the velocity and persistence of the current and the supply of sand. Also, like a river, the longshore stream may overflow. If we view the banks of the river as the beach and the surf zone, we realize that as water builds up in the longshore current, it must eventually "overflow" and return seaward. It does

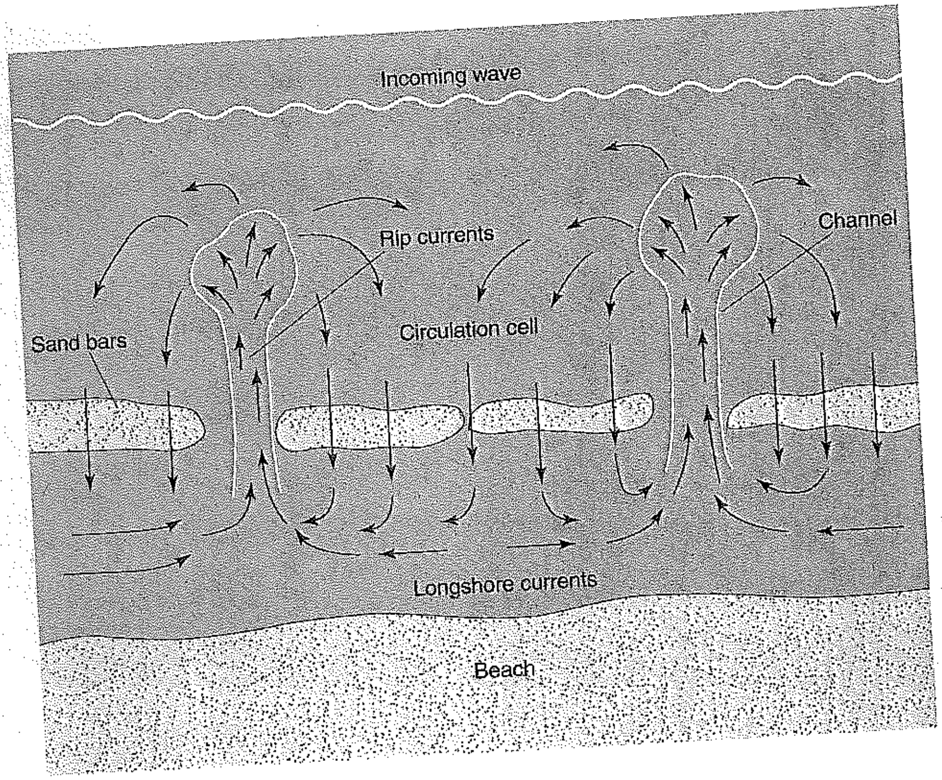


Figure 12-9 Diagram of the nearshore current system. [From R. A. Davis, Jr., *The Evolving Coast*, Scientific American Library, W. H. Freeman and Company. Copyright © 1997.]

so in the form of **rip currents,** improperly called rip tides, which can pose a formidable hazard to swimmers when the waves are high. They can be identified by the presence of a gap in the wave forms of the breakers, white foamy water extending seaward beyond the turbulence of the surf zone, and streaks of sediment or floating objects moving seaward in the rip (Figure 12-8). A diagram of the nearshore system of circulation and currents is shown in Figure 12-9.

The longshore current, unlike a river, may reverse its direction as a consequence of differing wave approaches, but it never stops flowing. Thus, where the supply of sand to a given point along the beach is less than the amount removed by longshore currents, erosion and loss of beach ensue. Although beach erosion may result from natural causes—such as drought, which decreases sand supply from rivers—coastal engineering works are more often directly responsible.

Structures of considerable height that extend seaward for some distance are effective barriers to littoral drift. But short groins are usually constructed for shoreline stabilization and only temporarily disrupt the longshore transport of sand (see Figures 12-10 and 12-11. Table 12-2 indicates the magnitude of the problem in southern California. Keep in mind that for every cubic yard of sand trapped or stored by a groin or breakwater, the beaches that are downcurrent are deprived of an equivalent amount, and the loss of beach width by erosion inevitably occurs. The same problem is also prevalent in the Great Lakes and along the East and Gulf coasts of the United States. The figures shown for accretion are even more striking when we consider that a cubic yard is roughly equivalent to 1 square foot of beach. That is, if 100,000 cubic yards of sand are lost, this volume is equivalent to beach retreat of about 1 foot along a length of 100 feet. It may be seen that if loss of

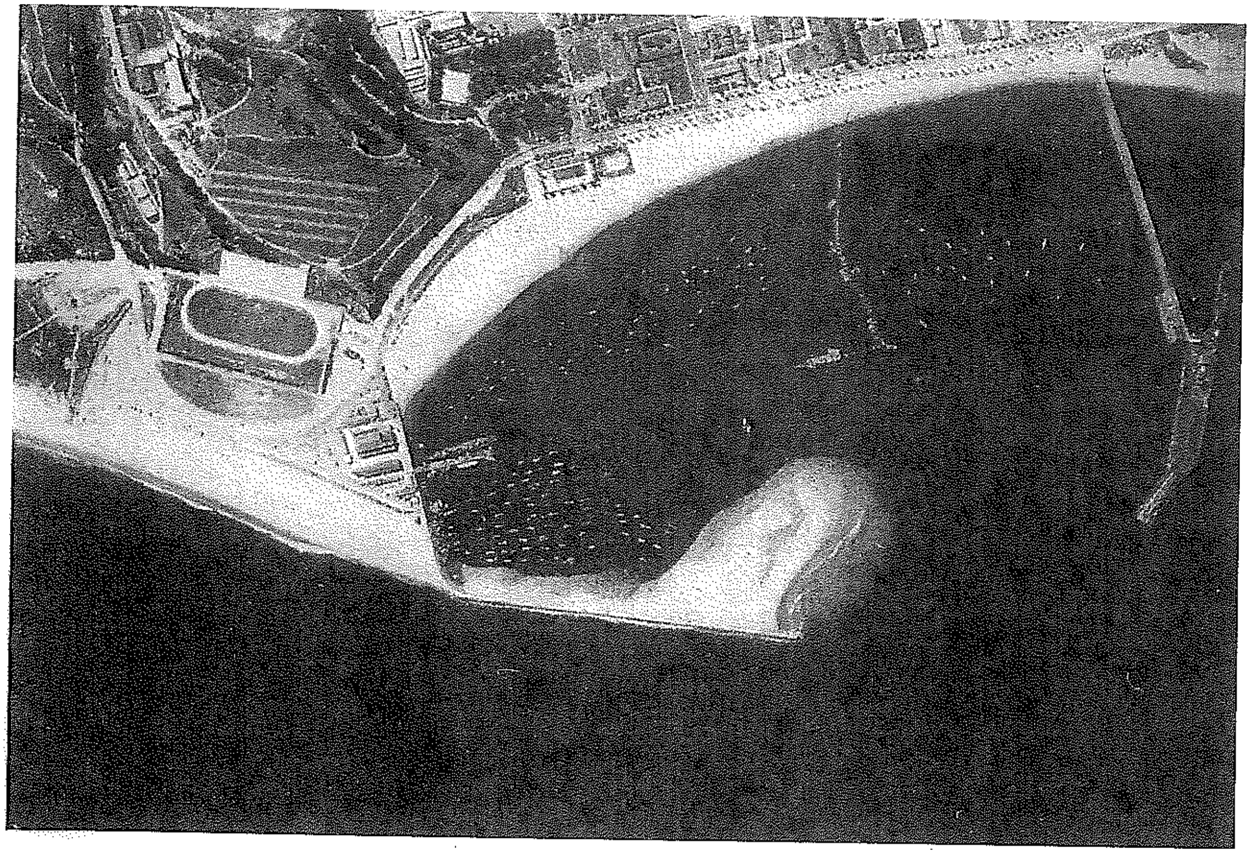


Figure 12-10 Breakwater at Santa Barbara, California, causes sand transported by longshore currents to be deposited as a sandbar in the lee of the breakwater. Sand must be periodically dredged from the harbor to beaches farther east (top of the photograph). [From W. Bascom, "Beaches." *Scientific American*. Copyright © 1960, Volume 203, Number 2, p. 90.]

sand continues for many years it can seriously diminish a recreational area. Finally, repair of the damage is costly.

Barrier beaches, also known as offshore bars, ring the entire East and Gulf coasts of the United States from New York to the tip of Florida to Padre Island, Texas. Atlantic City, New Jersey, Kitty Hawk, North Carolina, and Miami Beach, Florida are all examples of barrier beaches that are subject to inundation and extreme erosion during tropical storms and hurricanes (see Exercise 13). Miami Beach spent $10 million in the 1980s to dredge sand from offshore and place it along approximately 10 miles of city beach front. This replenished beach was washed back into deeper water by winter storm waves in just 3 years. An outstanding example of extreme erosion and loss of habitat is Hog Island, Virginia (Figure 12-12). In the late 1800s it was the site of lavish fishing and hunting clubs and was covered by a pine forest. A hurricane in 1933 inundated the island and destroyed the forest and town, which is now under water hundreds of meters from shore.

The natural transport of longshore drift is shown dramatically in three photographs of Sand Beach, New Jersey, taken over a period of 23 years (Figure 12-13a, b, and c). Note the growth of the spit within that period of time and the direction of the longshore current.

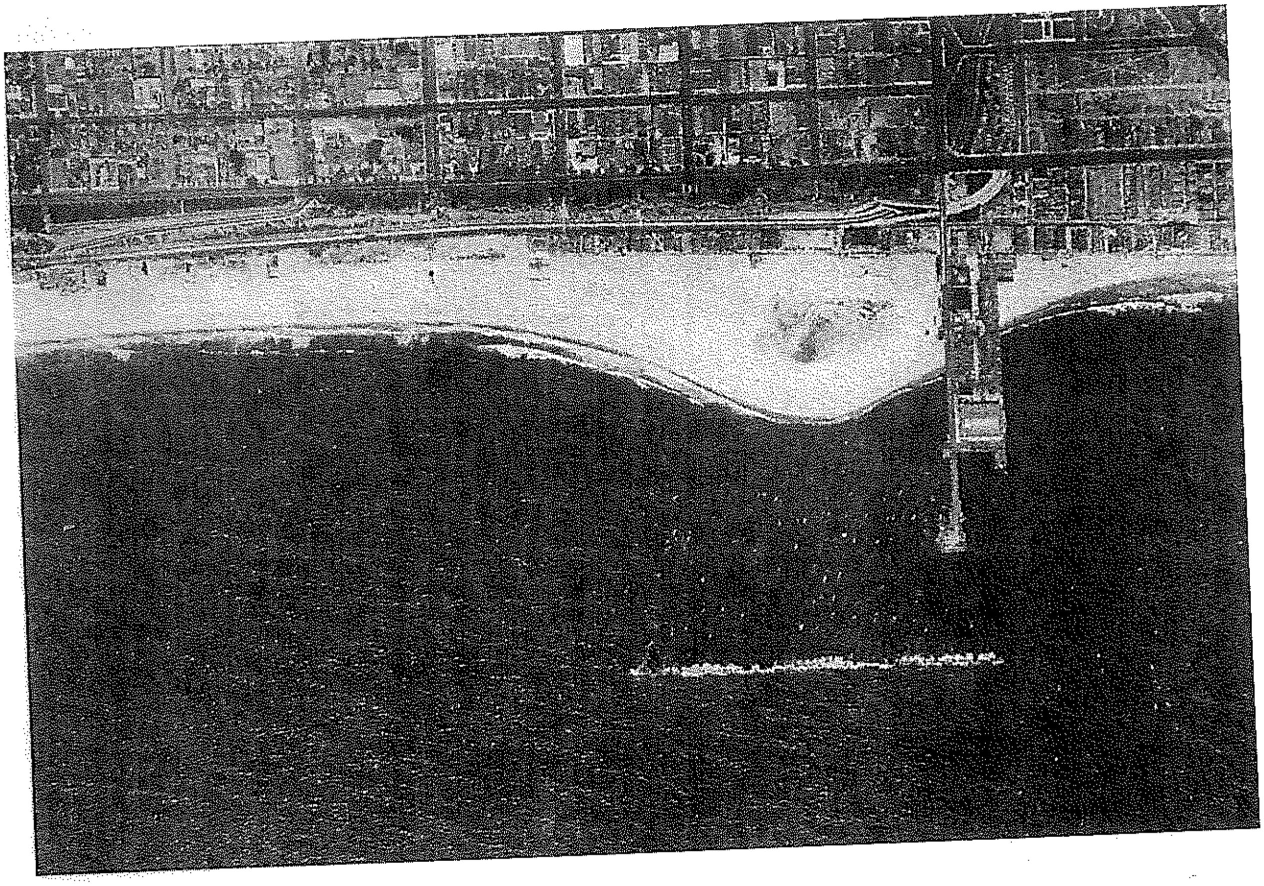


Figure **12-11** This breakwater at Santa Monica, California, runs parallel to the shoreline. Note the accumulation of sand behind the breakwater. [From W. Bascom, "Beaches." *Scientific American.* Copyright © 1960, Volume 203, Number 2, p. 86. All rights reserved.]

TABLE 12-2

Rates of littoral drift and accretion at shoreline structures for selected southern California localities

Location	Accretion rate (10^3 cubic yards per year)
Santa Barbara breakwater (Figure 12-10)	280
Santa Monica breakwater (Figure 12-11)	259
Redondo Beach	30
Anaheim Bay jetties	175
Balboa Bay jetty	72

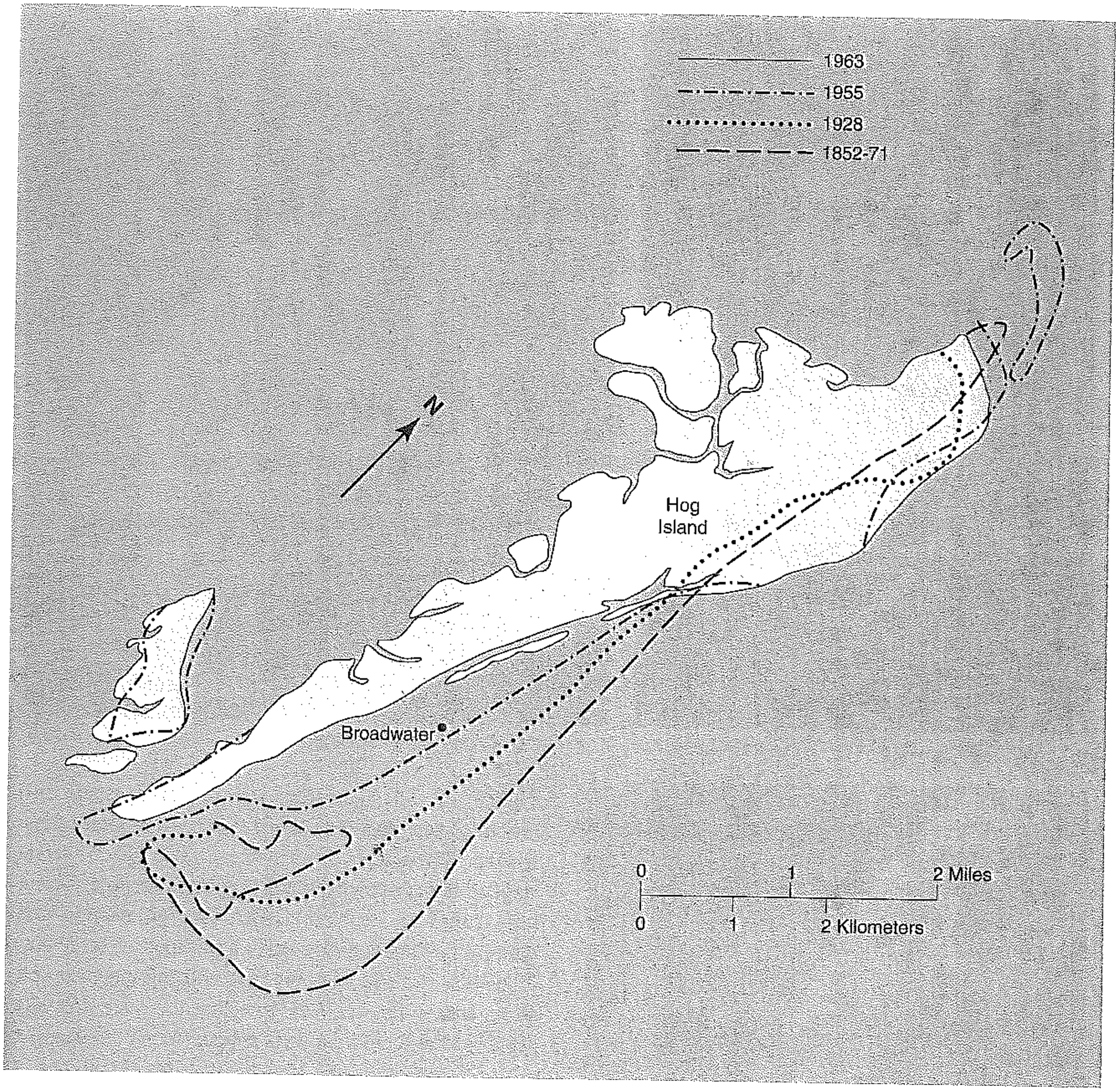
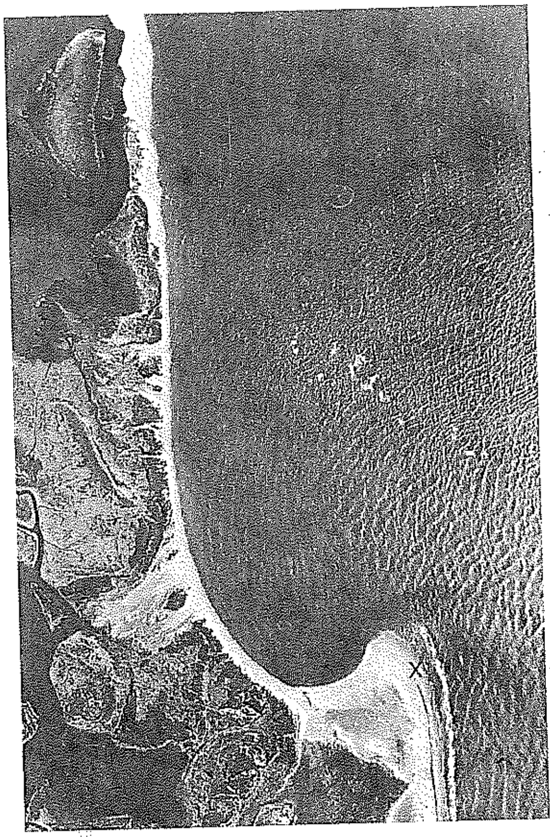


Figure 12-12 Hog Island is a prime example of extreme erosion of barrier islands along the east coast of the United States. The main town of Broadwater had a population of about 300, 50 houses, a lighthouse, cemetery, and school. A hurricane in 1933 overtopped the island, destroying much of the town and killing the protective pine forest. By the 1940s all inhabitants had left, and the town is now under several meters of water.



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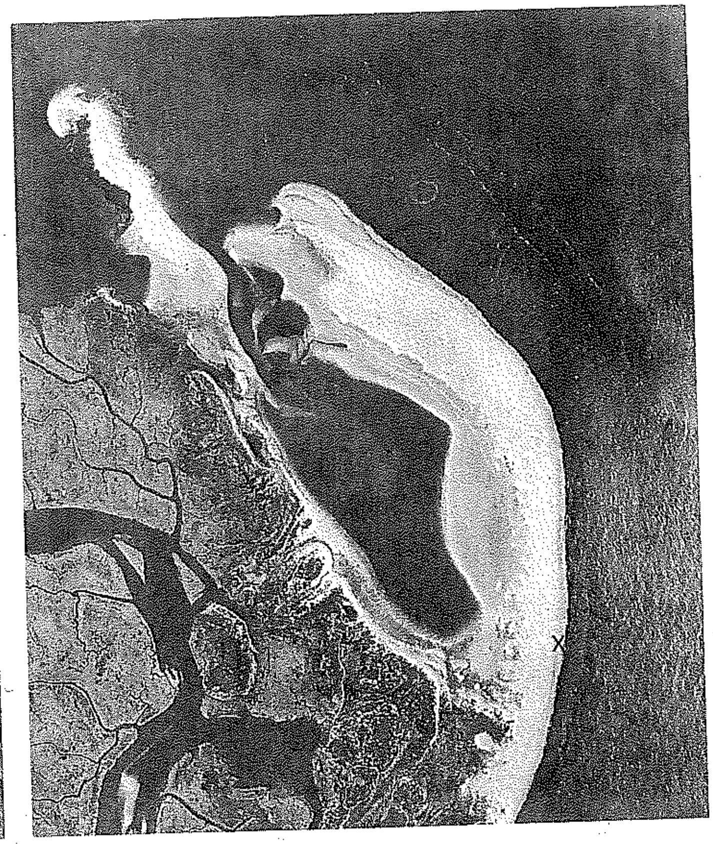

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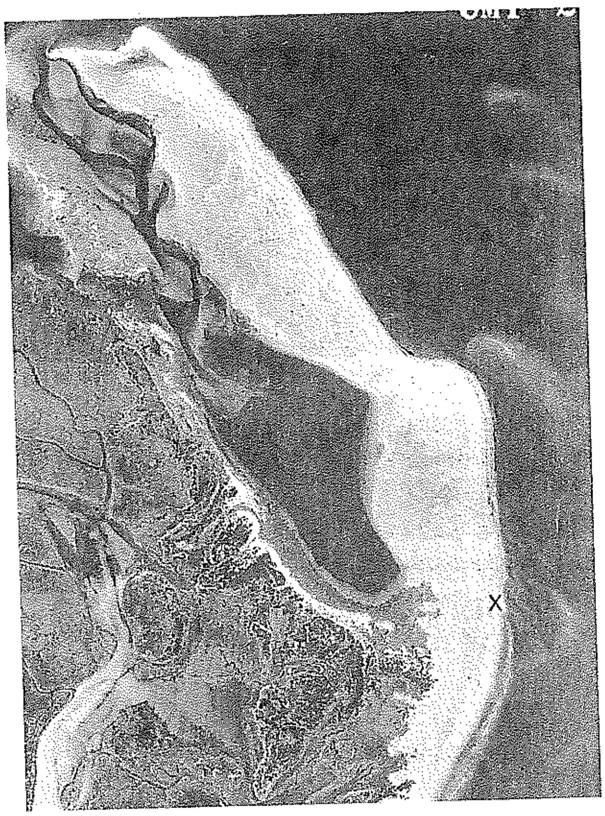

c

Figure 12-13 The natural transport of longshore drift over a 23-year period at Sandy Beach, New Jersey (designated by the cross in all photos). (a) 1940: The first stage in the development of a spit; the longshore current runs toward the north. (b) 1957: The spit extends with time in the direction of longshore transport of sediment. (c) 1963: The spit joins the land and the recurved spit grows around the tip. Also note that the main spit has screened the shore from wave action. [From C. S. Denny et al., *A Descriptive Catalog of Selected Aerial Photographs of Geologic Features in the United States.* U.S. Geological Survey Professional Paper 590, 1968]

DEFINITIONS

Littoral drift. The transport of sand, gravel, and other materials along the beach face by longshore (or littoral) currents.

Longshore (littoral) current. A current running parallel to the beach and generated by waves striking the shoreline at an angle.

Orthogonal. A line drawn perpendicular to wave crests so that refraction or bending can be visualized more clearly.

Reflection. The process by which the energy of wave is a returned seaward.

Refraction. The process by which the direction of a wave moving in shallow water at an angle to the bottom contours is changed. The part of the wave moving shoreward in shallower water travels more slowly than that portion in deeper water, causing the wave to turn or bend to become parallel to the contours.

Rip current. A current flowing seaward from the shore through gaps in the surf zone. The strength of the current is proportional to the height of the breakers striking the shoreline.

Surf zone. The nearshore zone along which the waves become breakers as they approach the shore.

Wave energy coefficient (e). Calculated as follows:

$$e = \frac{\text{width of orthogonals at shore}}{\text{width of orthogonals in deep water}}$$

Exercise 12

Report

Waves in Shallow Water and Beach Erosion

NAME ______________________

DATE ______________________

INSTRUCTOR ______________________

Refer to the appropriate figures in the text of this exercise to answer questions 1–4.

1. What is the direction of the longshore current and beach drifting in Figure 12-7? Answer in terms of left and right sides of the photo. ______________________

How did you determine this direction? ______________________

2. Examine Figure 12-10 and predict what will happen to Santa Barbara Harbor and the beaches downdrift if the harbor is not dredged and the sand moved downdrift of the pier. ______________________

3. Figure 12-14 depicts the nearshore oceanographic conditions at Santa Monica Beach, California (see also Figure 12-11). It should be noted that the pier is on widely spaced wooden pilings and has little influence on wave energy.

(a) Why has sand built out behind the breakwater? ______________________

(b) Indicate on the figure below the relative wave energy at points A–C. Use the terms *high, low,* and *nil.*

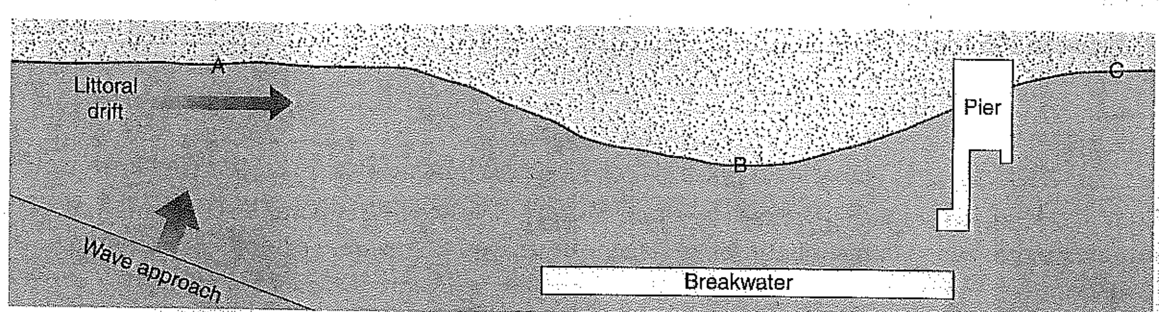

Figure **12-14** Diagram of a breakwater and beach at Santa Monica, California.

(c) Based upon the presence of the breakwater and wave direction shown in the figure, what condition of beach stability would you *predict* at point C: deposition, erosion, or no change? ______

However, the beach appears stable without erosion or deposition. How might this be explained? ______

4. Make a sketch of the wave refraction pattern around the small rocky island at Prouts Neck, Maine (Figure 12-4). Why does the beach extend farther seaward off the island than at adjacent areas?

5. Refer to the photos of Sandy Beach, New Jersey (Figure 12-13). (The right-hand side of the page is oriented directly north-south).

(a) What is the direction of wave approach? ______

(b) What is the direction of longshore drift? ______

(c) If the scale of all three photos is identical (1 inch = 2250 feet), how much has Sandy Beach grown between 1940 and 1957? ______

(d) Between 1957 and 1963? ______

6. Figure 12-15 shows wave-crest refraction shoreward. The dashed line at point Y represents a proposed breakwater, intended to complement the existing groin structure. Two wave orthogonals are sketched in for you.

(a) Sketch in orthogonals beginning at points 1, 2, 3, 4, and 5.

(b) Indicate along the shore in the diagram several places where you would expect the sand beach to become wider because of accretion, or to narrow because of erosion.

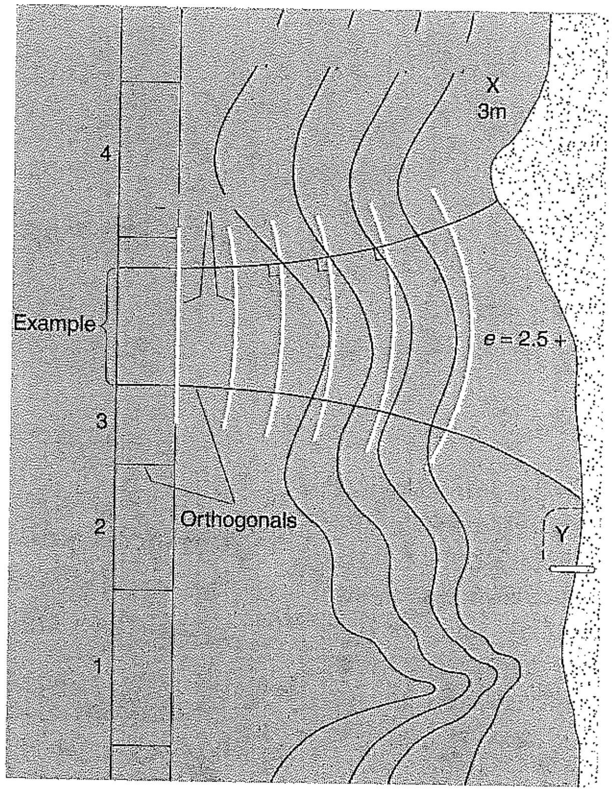

Figure **12-15** Wave refraction diagram for question 6. The numerals along the contour lines indicate water depths in meters. The wave energy coefficient, *e*, is 2.5 or more. Note the existing groin near point Y, and the dashed line indicating a proposed breakwater to be constructed next to the groin.

(c) What is the expected breaker height (in meters) at point X? ______________________

(d) Where would the best board surfing be found (biggest waves)? ______________________

(e) Where would the safest bathing beach be found? ______________________

(f) Sketch in the predicted wave refraction pattern over the submarine canyon.
What would be the expected direction of longshore currents north of the canyon, that is, between the head of the canyon and the groin structure near point Y? ______________________

(g) How would the longshore current affect the proposed breakwater at point Y? ______________________

7. Refer to Figure 12-12, Hog Island. How much did the shoreline retreat between the mapping performed in 1871 and that of 1963? __________ miles, __________ kilometers, __________ miles/year.